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Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height

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GUIDELINE FOR USE OF FLUID MODELING TO DETERMINE GOOD ENGINEERING PRACTICE STACK HEIGHT

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UNITED STATES ENVIRONMENTAL PROTECTION AGENCY
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1.0 INTRODUCTION

This guideline contains specifications for the use of fluid modeling to determine Good Engineering Practice (GEP) stack height. The guidance is intended for use by the U. S. Environmental Protection Agency (EPA), by State and local air pollution control agencies, and by industries and their consultants in the design and final review of a fluid modeling study determination of GEP stack height. The Agency issues guidelines in association with regulations in order to make clear any requirements for data and to present criteria the Agency will use in evaluating the adequacy of that data. The specifications in this guideline are necessary to assure consistency among studies. It is very important for both those conducting the fluid modeling study and those reviewing the results to share a common set of criteria for reference.

The aim of fluid modeling is to produce an accurate representation of the atmosphere using the flow of air or water in a test facility, e.g., wind tunnel or water channel. Certain similarity criteria must be considered if fluid modeling studies are to accurately reproduce atmospheric phenomena. A separate guideline entitled, "Guideline for Fluid Modeling of Atmospheric Diffusion," (Snyder, 1981), reviews the fundamental principles and practical applications of fluid modeling. The aim of that guideline is to establish the capabilities and limitations of fluid modeling, and to establish EPA standards for the conduct of fluid modeling studies. This guideline is based on Snyder's state-of-the-art review.

2.0 BACKGROUND

As required by Section 123 of the Clean Air Act Amendments of 1977, the Administrator has proposed regulations (Sections 1 and 18 of 40 CFR Part 51) to assure that the control of any air pollutant under an applicable implementation plan shall not be affected by (1) stack heights that exceed good engineering practice or (2) any other dispersion technique. Good engineering practice (GEP) is defined with respect to stack heights in Section 123 of the Clean Air Act Ammendments of 1977 as "the height necessary to insure that emissions from the stack do not result in excessive concentrations of any air pollutant in the immediate vicinity of the source as a result of atmospheric downwash, eddies and wakes which may be created by the source itself, nearby structures or nearby terrain obstacles."

The scientific literature, in general, indicates that a case-specific review is integral to assuring the prevention of adverse aero-dynamic effects in the immediate vicinity of a given source. However, the literature also identifies a general formulation that establishes a minimum height necessary to prevent significant effects of nearby structures. The GEP formulation is a reasonable working rule, defined as:

$$H_g = H + 1.5L \qquad (1)$$

where: H_g = GEP stack height

H = Height of the structure or nearby structure

L = Lesser dimension (height or width) of the structure or nearby structure.

The basis of the formulation and a summary of extensive scientific literature on the subject can be found in the "Guideline for Determination of Good Engineering Practice Stack Height" (EPA, 1980).

Proposed regulations (40 CFR Part 51) to implement Section 123 of the 1977 Clean Air Act Amendments allow the stack heights near structures as determined by Equation 1 to be used in some cases as the maximum creditable stack height which may be used in establishing a source's emission limitation for a State Implementation Plan. The GEP creditable stack height, based on nearby terrain features, must be determined on a case-by-case basis through the use of appropriate field or fluid modeling studies. Field or fluid modeling studies may also be used by the source operator to show that a stack height greater than determined by Equation 1 is needed to prevent excessive pollutant concentrations. This guideline is appropriate when fluid modeling is used to determine GEP stack height. An excessive concentration, for the purpose of determining GEP stack height, is defined in the regulation as a maximum ground-level concentration monitored or modeled in the presence of nearby structures or terrain obstacles that is 40 percent or more, in excess of the maximum ground-level concentration, monitored or modeled for the same orientation and stack parameters in the absence of downwash, wake, or eddy effects produced by nearby structures or terrain.

3.0 BASIC CONCEPTS

The basic concepts for designing a fluid modeling study are outlined in the following subsections. The construction of a fluid model requires that the flow in the test facility (e.g., wind tunnel) be appropriately fixed and along with the surface roughness, terrain, and/or buildings, scaled to accurately reproduce atmospheric phenomena. The stack and plume from the source must also be similarly scaled if dispersion patterns in the fluid model are to simulate those in the field. The fluid model encompasses the entire situation within the four walls of the test facility that is designed to accurately simulate atmospheric flow in the field. Consideration of each of the concepts outlined in the following subsections leads to requirements for data and the reporting of that data as given later in Section 4. Specific references to requirements given in Section 4 are underlined.

A detailed formulation and discussion of the fundamental principles for fluid modeling of atmospheric phenomena is presented by Snyder (1981). A summary of the important criteria is presented here. Certain similarity criteria must be considered if fluid modeling is to accurately reproduce atmospheric phenomena. The dynamics of the flow in the fluid model must accurately simulate those in the field. The effects of surface conditions in the field upstream of the modeled area must be accounted for in the fluid model by developing appropriate boundary layer conditions. The necessary surface roughness, terrain, and buildings are included in the construction of the fluid model. The plume trajectory in the fluid model must be similar to that in the field if air quality impact is to be evaluated.

The purpose of the fluid modeling study for determining GEP stack height is to demonstrate the stack height needed to avoid excessive concentrations caused by the effects from nearby structures or terrain obstacles as specified by stack height regulations. GEP stack height is appropriately determined for the situation under atmospheric conditions that result from those surface influences of highest extent.

Above some minimal reference wind speed, e.g., 3 m/s, the flow pattern near the structure or terrain obstacle in the field is independent of wind speed, as is reasoned in the discussion presented in Section 3.1 on Reynolds number independence. The greatest effect on the plume should occur when plume rise near the source is lowest. For most sources, even those with a relatively high exit velocity, high wind speeds found to occur occasionally at most locations will result in significantly reduced plume rise and thus the greatest potential for ground-level concentrations in excess of those in the absence of structure or terrain obstacle influences.

The wind speed that will result in the determination of greatest GEP stack height is seen for all foreseeable situations to exceed 6 m/s. The atmosphere is characterized by a generally neutral state of stability when the surface wind speed at a height of 10 m is greater than 6 m/s (Turner, 1970). Thus, the critical conditions of stability for determining GEP stack height are expected to be associated with a neutral (adiabatic) atmosphere. Specific guidance for fluid modeling of an adiabatic atmosphere is given herein. Guidance for modeling a nonadiabatic atmosphere is not provided; the need to model these situations requires case-by-case consideration.

To define GEP stack height for a specific stack, measurements in the wake of and in the absence of either the structure or terrain obstacle are needed to assess the increase in maximum concentrations. The concentration increase must be assessed to determine whether the increase constitutes an excessive concentration. Concentrations in the wake of the structure or terrain obstacle are considered excessive if the maximum ground-level concentrations are at least 40 percent greater than the maximum in the absence of their influences. Wind-tunnel modeling is ideally suited for this type of determination since the model structure or terrain feature being studied can be easily removed to assess its effect. More importantly, a properly designed wind-tunnel study can account for the aerodynamically induced influences affecting the dispersion of the stack effluent.

3.1 Dynamic Similarity Criteria

To rigorously model the dynamic behavior of atmospheric flow, five nondimensional parameters must be matched between the model and the field. These parameters, as discussed by Snyder (1981), are:

1. Froude number, $Fr = U_R / \sqrt{gL\delta T_R / T_o}$;
2. Rossby number, $Ro = U_R / L\Omega_R$;
3. Reynolds number, $Re = U_R L / \nu$;

4. Peclet number, $Pe = U_R L \kappa$;

5. Reynolds-Schmidt number, $Re\text{-}Sc = U_R L/\alpha$.

where:

U_R = reference velocity;

Ω_R = reference angular velocity;

L = reference length;

δT_R = temperature deviation from adiabatic atmosphere;

T_o = temperature of adiabatic atmosphere;

g = gravitational constant;

ν = kinematic viscosity (momentum diffusivity);

κ = thermal diffusivity;

α = molecular diffusivity.

The Froude number represents the ratio of inertial forces to buoyancy forces on a local air parcel. Calculation of the Froude numbers should be based on the measured temperature profiles. A large value of the Froude number implies that buoyancy forces are small relative to inertial forces. Thus, atmospheric flows having large Froude numbers are considered neutral (adiabatic). A truly adiabatic atmosphere has an infinite Froude number. <u>Isothermal flow must be maintained in the test facility to adequately model an adiabatic atmospheric flow</u>. This similarity criterion for fluid modeling of adiabatic atmospheric flow can be easily met by insuring that air in the room containing the facility and the fluid temperature in the test facility are equal. This is especially necessary when the flow speed through the test facility is slow. <u>Steps 2a and 3a of Section 4.1.3 are required to satisfy this similarity criterion</u>.

The Rossby number represents the ratio of the inertial forces to the Coriolis force on a local air parcel. Coriolis force results in the wind vector changing direction with increasing height above the surface. If the Rossby number is large, the Coriolis force is relatively small and thus does not have a significant effect on a dispersing pollutant. Snyder suggests that the Rossby number is sufficiently large at downwind distances (L) less than about 5 km to ignore Coriolis force for modeling dispersion in adiabatic atmospheric flow over flat terrain. No information is available to assess the effect of Coriolis force in regions of complex terrain. This implies that fluid modeling should be limited to areas within 5 km of the source, since Coriolis force cannot presently be simulated. Mathematical models of atmospheric dispersion in current use do not account for Coriolis forces. Therefore, while fluid modeling should be limited to areas within 5 km of the source, its use for modeling larger areas may as for mathematical models be similarly justified, when necessary. The Rossby number criterion is not a critical modeling parameter, although it poses a limitation on the use of fluid modeling. There are no special data requirements to satisfy this similarity criterion.

The Reynolds number represents the ratio of the inertial forces to the frictional forces on a local air parcel. When the modeling medium is air, the reference velocity must be increased by the same amount as the reference length is reduced in order to match the Reynolds number. In water, the reference velocity need only be increased by 1/15 the reduction in the reference length, since the kinematic viscosity of water is 1/15 that of air. However, using water as the medium requires much more energy for equal rates of flow. This physical limitation generally results in water tunnels having to be smaller in size and operated with lower flow rates than wind tunnels. The reference length in atmospheric dispersion problems must be modeled at a reduced scale of several orders of magnitude, making an equivalent increase in the reference velocity impractical. Thus if strict adherence to the Reynolds number criterion were required, no atmospheric flows could be modeled.

Various arguments to justify the use of smaller Reynolds numbers in fluid modeling compared to those in the atmosphere are found in the literature. The best argument appears to be the principle of Reynolds number independence. This principle is based upon the hypothesis that in the absence of buoyancy and Coriolis effects, the pattern of turbulent flow is similar at all sufficiently high Reynolds numbers. If the Reynolds number is large, frictional forces are relatively small compared to the inertial forces. For Reynolds number independence to hold, the frictional forces must remain relatively small and have little effect on the overall flow as the Reynolds number is decreased. A large amount of experimental evidence now exists to support this principle. For atmospheric flows, Reynolds number independence appears to apply except in the very smallest scale of the turbulent flow very close to the ground or other physical boundary. In effect, the reference length L (scale of flow structure examined) is small where the frictional forces are important. Flow very near structures or terrain features may not be Reynolds number independent.

Practice indicates that sufficiently large Reynolds numbers are attainable at least for modeling the flow over sharp-edged geometrical structures or terrain features in ordinary meteorological wind tunnels. However, more work must be done to determine if simulation of flow over more streamlined surfaces can be sufficiently modeled. Frictional forces have very little effect if the general flow is detached from the surface or other physical boundary. Flow over streamlined surfaces is less susceptible to detachment and thus is more sensitive to the value of its Reynolds number. Reynolds numbers in atmospheric flow generally are sufficiently large for the independence principle to hold. Fortunately, flow similarity is generally observed at the lower values of Reynolds number attainable in fluid modeling, provided the flow is locally detached or if the area of study is sufficiently above the surface. This has led modelers in some situations to force flow detachment by adding roughness to the model structures or terrain features. <u>The Reynolds number criterion is a critical modeling parameter. Step 4 in Section 4.2.1 requires a test for Reynolds number independence.</u>

The Peclet number is most easily discussed by writing it as the product of the Reynolds Number and Prandtl Number:

$$Pe = \frac{U_R L}{\nu} \frac{\nu}{\kappa} = Re \cdot Pr.$$

The Reynolds-Schmidt Number can similarily be written as the product of the Reynolds Number and the Schmidt Number:

$$Re\text{-}Sc = \frac{U_R L}{\nu} \frac{\nu}{\alpha} = Re \cdot Sc.$$

Both the Prandtl number and the Schmidt number are properties of the fluid. The Prandtl number is the ratio of the momentum diffusivity to the thermal diffusivity. The Schmidt number is the ratio of the momentum diffusivity to molecular diffusivity. These numbers are somewhat different between air and other fluids. This would seem to preclude using any model medium other than air in simulations of atmospheric flow. A high Reynolds number is necessary in the wind tunnel flow to match the Peclet number or Reynolds-Schmidt number found in the field. Arguments similar to those constructed for Reynolds number independence are used to justify the neglect of the Peclet number and Reynolds-Schmidt number as modeling criteria, provided the Reynolds number is sufficiently large. Both heat and mass are regarded as passive quantities in connection with most environmental atmospheric dispersion problems. Thus, if the Reynolds number of the main structure of the flow is sufficiently large, advection and the larger scale turbulent motions are totally responsibile for the transport and dispersion of a passive pollutant. That is, molecular or thermal diffusion acts mostly to smooth out the very small-scale discontinuities of concentration or temperature. <u>Molecular or thermal diffusion is assumed to contribute negligibly to the dispersion of the source plume within the</u> simulated <u>turbulent atmospheric boundary layer, provided the Reynolds number is large enough with the Peclet number and Reynolds-Schmidt number being themselves unimportant.</u>

3.2 Boundary Layer Conditions

The effects of upstream surface conditions on the velocity of the wind result in a variation with height described generally by some theoretical distribution such as a logarithmic or power law profile. The profile is characterized by the depth of the boundary layer and a representative surface roughness length. Turbulence intensity of the wind naturally decreases with height above the surface roughness. The profiles of mean velocity and turbulence intensity are very significant characteristics that should be very closely matched in the model.

Measurement of vertical profiles of Reynolds stress throughout the region of interest is especially useful in characterizing the surface friction velocity u_*, which is a parameter used in representing the velocity near the surface by a logarithmic profile. Measured profiles in the field will not likely be available at most sites where GEP stack height is to be determined. In Section 4, general modeling criteria are 3b, 3c in Section 4.1.3 requires mean velocity, turbulence intensity, and Reynolds stress profiles to be measured at several positions throughout the model.

Consideration of additional flow characteristics of the atmospheric boundary layer would be desirable. However, specific guidance is not possible. The purpose of specifying necessary modeling criteria for the boundary layer is to first insure that dispersion throughout the modeled flow correctly provides dispersion patterns comparable to those given by recommended air quality modeling techniques as described in the Guideline on Air Quality Models (EPA, 1978). Concern for the similarity of additional flow characteristics is not necessary if the model boundary layer dispersive characteristics are documented through measurements in the test facility to fall between estimated values for Pasquill-Gifford stability category C and D as prescribed by Turner (1970). Step 4 in Section 4.1.3 requires documentation of dispersion from the source.

A documentation and test of comparability of the fluid model boundary layer conditions to flow over flat terrain in the absence of any buildings can be done simply. Problems, however, arise in doing the same for flow over complex terrain or over urban areas where local differences near the surface result from different surface features. Because of these differences one cannot establish that the fluid model boundary is nondeveloping or that the dispersive characteristics can be represented by a general categorization. In order to evaluate the fluid model boundary layer conditions, it is necessary to first document the flow in absence of the complex terrain or urban structures as prescribed above. Differences found for flow over the complex terrain or urban area can then be related to the increased surface roughness. Section 4.2.1 requires measurements sufficient to document such differences.

3.3 Surface Roughness, Terrain, and Building Scaling

Minute geometric details of terrain or structures do not significantly affect atmospheric flow. Thus, such detail need not be considered in a fluid modeling simulation. Objects about the same size as the characteristic surface roughness length need not be produced in geometrical form but an equivalent roughness must be established. For example, gravel can be added to the surface of the terrain or buildings to establish an equivalent roughness.

Major terrain features and building structures must be scaled without geometric distortion. The amount of reduction in scale is limited by the requirement for the flow to be Reynolds number independent. Discussion and some guidance on selecting the proper model surface roughness, terrain height and building height are given by Snyder (1981). The fluid modeler's decisions must be based on a number of interacting concerns, including the size of the area to be modeled, the necessary boundary layer depth, the desired diffusion characteristics, and Reynolds number independence. Often, the fluid modeler's experience is the best guide. Data requirements and criteria which EPA will use to evaluate the resulting study are given in Section 4. It is recognized that each fluid modeler may have somewhat different approaches to selecting these design parameters. This is acceptable if the results meet the report requirements. <u>Section 4.1.1 outlines the requirements for modeling the surface and its boundary layer</u>.

3.4 Plume Rise

The atmospheric conditions that are considered here in determining GEP stack height are characterized as neutral stability (adiabatic) with high mean wind speed. Under such conditions, plume rise near the source where its rise is dominated by momentum flux will be small while its rise farther downwind may be largely due to buoyancy flux. A thorough review of the issues relating to fluid modeling of plume rise is presented by Snyder (Section 3.1, 1981).

In general, plume rise near the source in an adiabatic atmosphere has proven to be well-described for most conventional sources by the Briggs (1975) formulation,

$$\left(\frac{\Delta h}{H_s}\right)^3 = \frac{3}{\beta_1^2}\left(\frac{\rho_s W_s^2}{\rho_a U^2}\right)\left(\frac{D^2}{4H_s^2}\right)\frac{x}{H_s} + \frac{3}{2\beta_2^2}\left(\frac{gD^2 W_s(\rho_a - \rho_s)}{4\rho_a U^3 H_s}\right)\left(\frac{x}{H_s}\right)^2 \qquad (2)$$

$$= \frac{3}{\beta_1^2}\left(\frac{L_m}{H_s}\right)^2 \frac{x}{H_s} + 4.17\left(\frac{L_B}{H_s}\right)\left(\frac{x}{H_s}\right)^2$$

for $\beta_1 = 1/3 + U/W_s$, $\beta_2 = 0.6$ where L_m is a momentum length scale and L_B is a buoyancy length scale, defined as

$$\frac{L_m}{H_s} = \frac{1}{2}\left(\frac{\rho_s W_s^2}{{}_a U^2}\right)^{1/2}\frac{D}{H_s} \qquad (3)$$

$$\frac{L_B}{H_s} = \frac{1}{4}\left(\frac{1}{Fr_s^2}\right)\frac{D}{H_s}\left(\frac{W_s}{U}\right)^3\left(\frac{\rho_s}{\rho_a}\right) \qquad (4)$$

$$= \frac{1}{4}\left(\frac{1}{Fr_a^2}\right)\left(\frac{D}{H_s}\right)\left(\frac{W_s}{U}\right)^3$$

where:

ρ_s = stack effluent density

ρ_a = ambient air density

W_s = stack effluent exit speed

D = stack exit diameter

H_s = stack height

U = mean wind speed at height of stack

x = streamwise coordinate

g = acceleration due to gravity

$$Fr_s = W_s/[gD(\rho_a-\rho_s)/\rho_s]^{1/2}$$
$$Fr_a = W_s/[gD(\rho_a-\rho_s)\rho_a]^{1/2}$$

The first term in Equation 2 represents the contribution due to source momentum and the second term represents the contribution from source buoyancy. Close to the stack, the initial momentum term will be important, whereas, the buoyancy term in most cases will ultimately dominate. Matching the parameters in the above plume rise equation should insure comparable plume rise in the fluid model so long as the plume is not downwashed into the wake of the stack, buildings, or elevated terrain.

A GEP stack height determination must examine the effect of the nearby structure or terrain obstacle on the plume from the source. GEP stack height is limited to the height necessary to avoid excessive concentrations as explained in Section 2. Immediate plume rise near the source may in some situations significantly effect the stack height necessary to avoid the most adverse effects. The model study must be designed to demonstrate plume rise near the source to be comparable to the estimate by Equation 2 in the absence of buildings or terrain. This can be satisfied by correctly modeling the momentum length scale as presented in Section 4.1.2. EPA has based its definition of "excessive concentrations" on model results for sources not having significant plume rise downwind from the stack and thus the demonstration will be consistent. The model study design is considerably simplified by not having to model the buoyancy length scale which generally controls the resulting plume rise further downwind of the source. Also the results of the fluid model study will be generally more reliable.

When stack downwash occurs, special consideration must be given to the flow around the stack. It is essential to assure that the flow within the boundary layer around the stack is turbulent. Common practice in fluid modeling is to use a trip wire or fence or other surface roughness to force the boundary layer flow to be turbulent. This is not necessary for modeling rectangular stacks since their sharp corners force flow separation. In all cases, it is necessary to assure that the stack effluent exhaust is fully turbulent. Data requirements and criteria that EPA will use to evaluate the representativeness of the plume rise in the fluid model are presented in Section 4.1.2.

3.5 Concentration Measurements

Concentrations measured in a fluid modeling study should be related to those in the field through the nondimensional concentration, $C = \chi U H^2/Q$ as presented by Snyder (Section 3.5, 1981), where

χ = mass concentration of pollutant (gm/m^3),

U = reference wind speed (m/s),

H = characteristic length (m), and

Q = pollutant emission rate (gm/s).

The sampling time for measurements taken as part of the fluid modeling study must be long enough to provide steady-state averages. Fluid modeling is designed to correspond to conditions in the field for which the wind direction is steady. It is essential that the maximum ground-level concentrations be shown to represent the steady-state average values since they are crucial in the demonstration of excessive concentration. Data requirements and criteria which must be considered in establishing this fact are presented in Section 4.

In absence of effects of building and/or terrain, the pattern of concentrations in the fluid model should be comparable to those estimated by mathematical models recommended by EPA. Steady-state average concentration measured in the fluid model should thus correspond to one-hour average concentrations in the field. In those situations where persistence of the wind direction can be assumed, fluid modeling can be used for estimating average concentrations for longer periods of time. Fluid modeling studies can also be used for estimating average concentrations for periods having variability in the wind direction by including a separate examination of the flow for several directions. Concentrations can then be estimated by considering the frequency of wind direction.

4.0 REQUIREMENTS FOR A FLUID MODEL DEMONSTRATION

Section 3 presented a summary of the basic design concepts used in developing a fluid modeling study that is comparable to field conditions. Elements necessary for determining a GEP stack height are specified in this section. Specific guidance on requirements for data and the reporting of that data are given. Fluid modeling studies can be adapted to meet detailed specifications since essential characteristics can be controlled. Atmospheric flow is extremely complex in that profiles of its characteristics can vary with time and space. In general, profiles in the field rarely are available at the sites where a GEP stack height is to be determined. Therefore, it is only necessary for the modeling study to be designed to meet the general atmospheric conditions, given here as comparable to those used in air quality models recommended by EPA. Where detailed field information describing the situation is available, the modeling study should be designed to best assimilate it. For these situations, the fluid model should be shown to be comparable to the field.

The requirements given here are based on the general guidance by Snyder (1981). Readers and users of this guideline should be familiar with the presentation by Snyder. Deviation from his general guidance occurs in this guideline in a few instances where the objectives were judged to be met without additional detail.

Section 4.1 presents important criteria that should be considered prior to the construction of the fluid model for the actual situation.

The model scale should first be determined. Then a test for atmospheric dispersion comparability should be conducted as specified. Section 4.2 specifies the procedure and reporting requirements for determining GEP stack height. The step-by-step procedure leads simply to a satisfactory study provided sufficient preliminary consideration is given to the criteria presented in Section 4.1.

Specific reporting requirements presented here should be followed as outlined. All supplementary data taken as part of the study should also be incorporated into the report. A separate appendix describing the fluid modeling facility and instrumentation used in the conduct of the study should be attached. Normal operating conditions and associated parameters should be described. A daily log should be kept during the conduct of the study since the Agency may wish to conduct an audit and review. Since on-site visits and demonstration of repeatability of some measurements may be requested as part of quality assurance procedures, a proposed plan of study must be sumbitted to the reviewing Agency.

4.1 Preliminary Design

4.1.1 Model Surface and its Boundary Layer

The size of all building structures and the general topography in the vicinity of the source should be examined and the area to be determined. A roughly cubical building or other major structure, or a three-dimensional hill upstream of the source should be included if its height exceeds 1/20th of the distance from the source. An obstruction whose crosswind dimension is large compared to its height (width greater than 10 times its height) should be included if its height is greater than

1/30th of its distance upstream. For tall obstructions (height greater than width), the width replaces the height scale in the above determination of the critical distances. If possible, ridges even farther upstream should be included. In areas having undulating terrain, the hill or ridge height is defined as the elevation difference between its peak and local trough. A detailed topographic map and discussion concerning the selection of the size of the modeled area should be presented in the study report.

Additional parameters and criteria should also be considered in the selection of the scale of the modeled area. At this stage of experimental design, the fluid modeler should select design parameters that can be shown to satisfy necessary requirements. The fluid modeler's experience is likely the best guide in planning the study.

1. The buildings, other structures, and/or terrain should be immersed in an appropriate boundary layer that can be characterized as representing atmospheric dispersion between that for Pasquill-Gifford category C and D over flat terrain (Turner, 1970). The depth of the model boundary layer, δ, should be scaled to represent 600 m above the general level of terrain in the field, independent of surface roughness and wind speed. The depth of the model boundary layer is not critical so long as the boundary layer up to the level of the stack and its plume are scaled appropriately. The design wind speed will not be considered excessive so long as the speed is less than the speed that is exceeded less than 2 percent of the time (i.e., 98th percentile wind speed). This should be based on frequency distributions from at least one year of wind records representative of the source location. A frequency distribution

based on categories of specific design wind directions would only be appropriate if on-site meteorology is used. Wind speeds greater than the 98th percentile speed could be justified if air quality violations are a problem at higher wind speeds. In most cases, the wind records must be extrapolated to estimate the wind speed at stack height. The reviewing agency should determine the availability of appropriate wind records and their appropriate extrapolation to stack height.

2. The surface roughness length z_o and the friction velocity u_* should be derived from the mean velocity profile:

$$\frac{U}{u_*} = 2.5 \ln \frac{z-d}{z_o}, \qquad (5)$$

in the range, $1.5h_r \leq z \leq 1.5h_r + 100$ m, where z is the height, h_r is the general height of the surface roughness elements, and d is the displacement height (neglected for $z_o<0.2$ m, full scale). Simiu and Scanlan (1978) suggest that reasonable values of d in cities may be estimated using the formula

$$d=\overline{H}-z_o/k, \qquad (6)$$

where $\overline{H}$ is the general roof-top level and k is the von Karman constant (0.4). Values of the surface roughness length, z_o, for various types of surfaces are presented in Table 1 as a guide for a comparison. Actual values over urban areas with tall buildings or near elevated terrain may be substantially larger. Values of the friction velocity, u_*, are dependent on the value of z_o. Values for u_* as suggested by Counihan (1975) are presented in Figure 1, as a guide for a comparison.

Table 1. Values of Surface Roughness Length (z_0) for Various Types of Surface (from Simiu and Scanlan, 1978).

Type of Surface	z_0 (cm)
Sand	0.01 - 0.1
Sea Surface	0.003^a - 0.5^b
Snow Surface	0.1 - 0.6
Mown Grass (∿0.01m)	0.01 - 1
Low Grass, Steppe	1 - 4
Fallow Field	2 - 3
High Grass	4 - 10
Palmetto	10 - 30
Pine Forest (Mean height of trees: 15m; one tree per $10m^2$; $z_d \simeq 12m$)	90 - 100
Outskirts of Towns, Suburbs	20 - 40
Centers of Towns	35 - 45
Centers of Large Cities	60 - 80

[a] Wind speed at 10m above surface = 1.5m/sec.

[b] Wind speed at 10m above surface > 15m/sec.

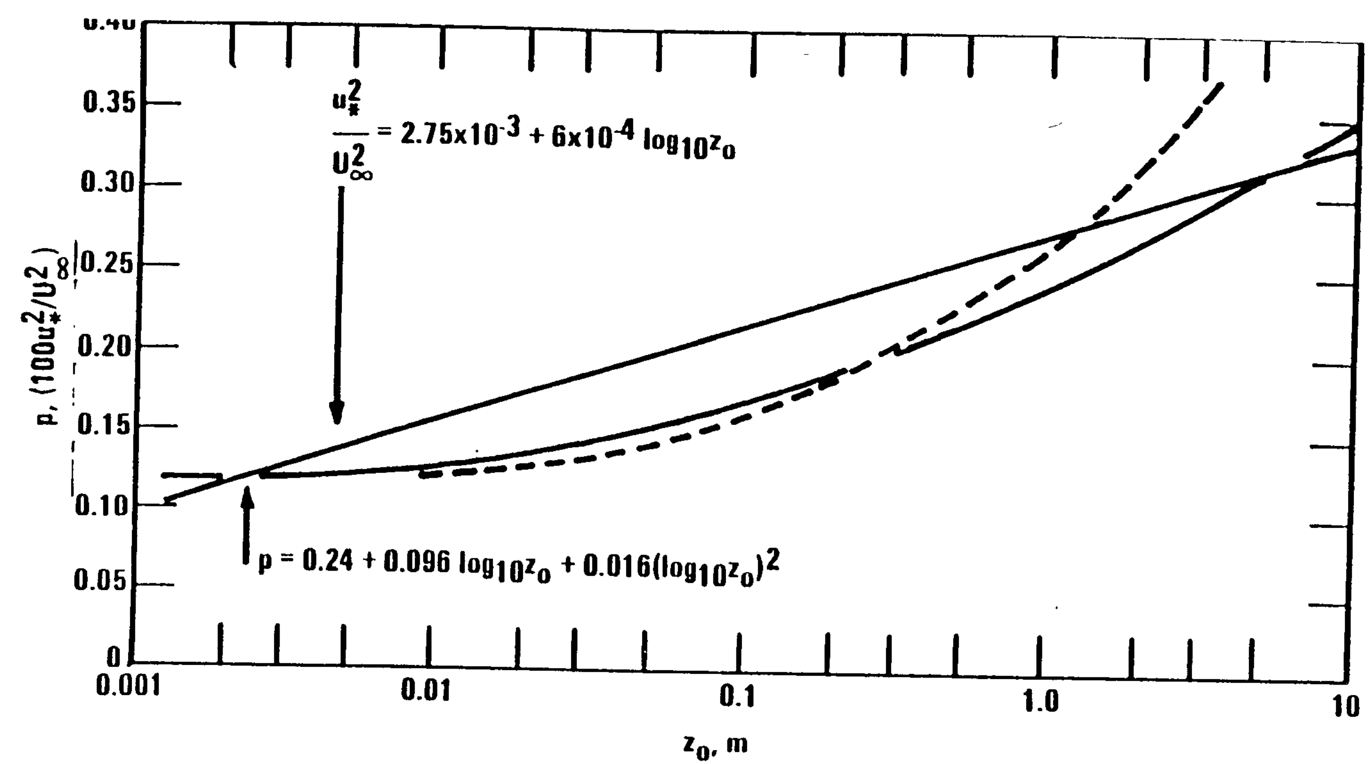

Figure 1. Variation of power law index p, and surface friction velocity u_*, with roughness length z_0 in the adiabatic boundary layer from Counihan (1975). Dashed curve is power law index from Irwin (1979).

The vertical profile of $-\overline{uw}$ (i.e., the correlation between the fluctuating velocity in the streamwise and vertical directions) may also be used to estimate the value of u_* as demonstrated in the example of Figure 2. The value of u_* is equal to the value of a $-\overline{uw}$ at the surface which should be based on the entire profile.

3. The mean velocity profile through the entire depth of the boundary layer should be represented by a power law $U/U_\infty = (z/\delta)^p$. The power law index p is dependent on the value of z_0. Values for p as suggested by Counihan (1975) and Irwin (1979) are presented in Figure 1, as a guide for a comparison.

4. The surface of the model should be covered with roughness of size ε such that $\varepsilon u_*/\nu \geq 20$, as suggested by Snyder (1981). Similarily, the step size in "stepped" terrain models should be of order ε and surfaces of buildings or other structures should be covered with roughness of size ε. Compromises may be appropriate for surfaces having sharp edges. For sharp-edged surfaces, the flow is separated and likely not significantly affected by roughness on its surface. Protuberances in the terrain, buildings, or other structures less than the size ε need not be reproduced in detail in the model. Similarly, details in the flow and dispersion pattern are not reproduced for scales less than the size ε.

5. The flow over significant elevated terrain, buildings or other structures nearby the source is Reynolds number independent. For design purposes, a minimum Reynolds number $U_H L/\nu$ greater than 11,000 is taken here as sufficient without demonstration for sharp-edged obstacles. The

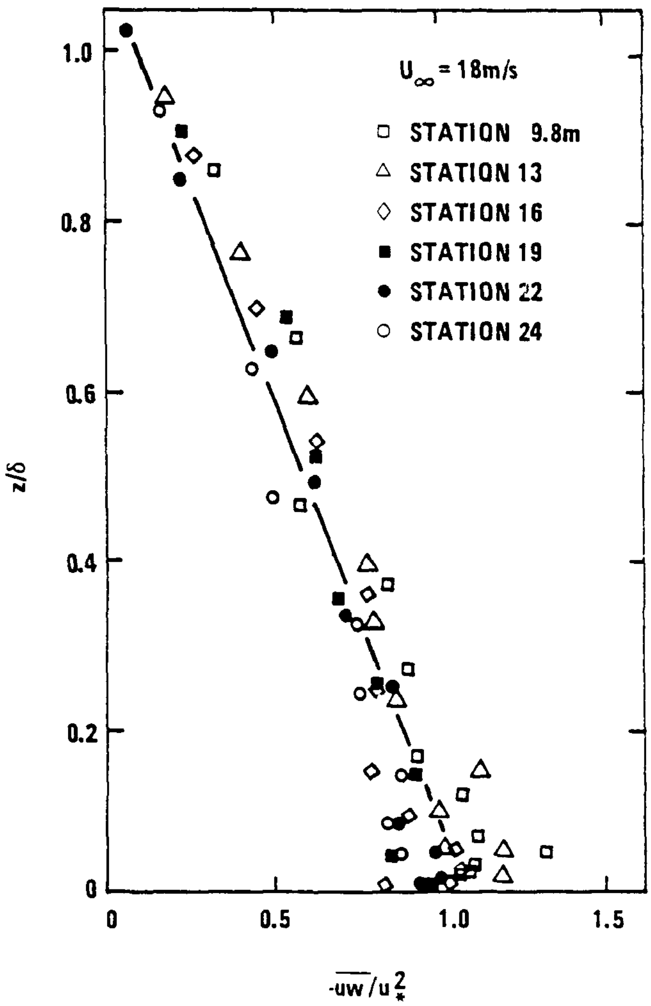

Figure 2. Variation of shear stress with height measured at various downwind positions in a wind tunnel boundary layer (adiabatic flow). Data from Zoric and Sandborn (1972), (as in Snyder 1981).

reference velocity U_H is the mean velocity upstream at the height of the obstacle and the reference length L is its lesser dimension (height or width). A test of Reynolds number independence should be conducted when significant effects of flow over terrain or smooth-shaped obstacles are being considered.

6. Blockage of flow (i.e., the ratio of cross-sectional area of a model to the cross-sectional area of the test section) is limited to a percent for an ordinary wind tunnel and to 10 percent in a tunnel with a properly adjusted ceiling.

4.1.2 Plume Rise

The Briggs (1975) formulation as presented in Section 3.4 is adopted here to provide an estimate of the plume centerline height for the source in the field. The GEP demonstration requires only that the stack effluent density, exit speed, and diameter be appropriately scaled to model the momentum length scale as discussed in Section 3.4. Vertical profiles of concentration through the plume centerline can be used to provide a measurement of the elevated centerline height in the fluid model, where reflection from the surface, and influences from terrain, buildings or other structures are not significant. The measured elevated plume centerline height should be comparable to estimates as discussed in Section 3.4. In all cases the plume height in the model should be representative of plume rise in the field near the stack. However, the plume height farther downwind of the source will not be representative of plume rise in the field for highly buoyant sources.

The exhaust from stacks is usually fully turbulent in the field. The effluent Reynolds number cannot be matched to assure similarity. It is sufficient, however, for the fluid model effluent Reynolds number to exceed a critical value following the arguments of Reynolds number independence. The fluid model stack effluent Reynolds number, $W_s D/\nu$, should be guided (in order of decreasing "correctness") by the following:

(a) Fix the effluent Reynolds number to be as large as possible, preferably greater than 15,000.

(b) If it is necessary to reduce the effluent Reynolds number below 2,000, trip the flow to ensure a fully turbulent exhaust. A smoke visualized effluent should be used to demonstrate a fully turbulent exhaust.

(c) If it is desired to reduce the effluent Reynolds number below 300, it will be necessary to do some experimentation to determine under what conditions the plume will simulate the behavior of a plume in the field.

Plume rise must be fixed by matching each of the following ratios:

$$\frac{W_s}{U_s};\frac{\rho_s}{\rho_a};\frac{D}{H_s}$$

which results in matching the momentum length scale. To model situation with stack effluent downwash around the lip of the stack, the flow within the boundary layer around the stack must be turbulent.

4.1.3 Atmospheric Dispersion Comparability

In the absence of buildings, other surface structures, or large roughness and/or elevated terrain, dispersion in the fluid model must show comparability to that described for the atmosphere by the basic Gaussian plume distribution (Turner, 1970). Concentration measurements for this test of comparability must be compared with values representative of field estimates given between estimates for Pasquill-Gifford category C and D. The procedure for demonstrating this comparability is outlined below. The purpose of this test is to provide an evaluation of the model flow in absence of buildings, other surface structures or large roughness, and/or elevated terrain. This test will insure that each study shares some common ground and demonstrates comparability to recommended modeling techniques for atmospheric dispersion over flat terrain (EPA, 1978).

Step 1:

(a) Select model scale and the model flow velocity. In choosing the scale, consideration should be given to all criteria as outlined in Sections 4.1.1 and 4.1.2 The flow velocity should be matched at the height of the proposed stack.

(b) Select the position where the model stack will be placed.

(c) Select the method for providing a fully developed and appropriate boundary layer at and downwind of the stack.

(d) Report a detailed description of the fluid model.

Step 2:

(a) Measure the mean temperature θ (°K) near the model surface and at several positions within the freestream flow. Additional profiles are necessary if operating conditions change. These measurements are not necessary if model freestream speeds exceed 3 m/s and the facility is temperature controlled during the study.

(b) Take vertical profiles of the mean velocity U (m/s), and the longitudinal turbulence intensity $(\overline{u^2})^{\frac{1}{2}}/U$, vertical turbulence intensity $(\overline{w^2})^{\frac{1}{2}}/u$, and $\overline{-uw}$ (m^2/s) near the position where the stack will be placed, downwind at the end of the planned study area, and midway between these two positions (3 profiles each).

(c) Take lateral profiles of the mean velocity and longitudinal turbulence intensity along the model surface and two elevated profiles bracketing the range of plume heights evaluated in the study near the position where the stack will be placed and near the end of the planned study area (4-6 profiles each).

Step 3:

(a) Report and evaluate the temperature profiles. The profile of mean temperature should be uniform. A deviation from a uniform profile would indicate that air within the facility building is not well mixed.

(b) Report and evaluate the velocity profiles. Report the vertical profiles of mean velocity on log-linear scaled paper and estimate the values for the effective surface roughness length z_o and the friction velocity u_* at each position, per Equation 5. Estimate these values by determining the best fit to the data representing the lowest 100 m, full scale, above the height of the surface roughness elements. Replot the profiles of mean velocity on linear scaled paper and estimate the power law index p. The model values of z_o, u_*, and p should be consistent with guidance presented in Table 1 and Figure 1, representing atmospheric flow over flat terrain with z_o<0.2 m and δ = 600m. Report the profiles of turbulence intensity. Figure 3 is presented for consideration to be used as a guide. Values of turbulence intensity representative of conditions in Figure 3 fo z_o>0.2 m may indicate the model flow is too turbulent. The best test lies with the evaluation of concentration measurements as discussed below. The profiles of mean velocity and profiles of turbulence intensity should all be similar throughout the study area. Significant differences

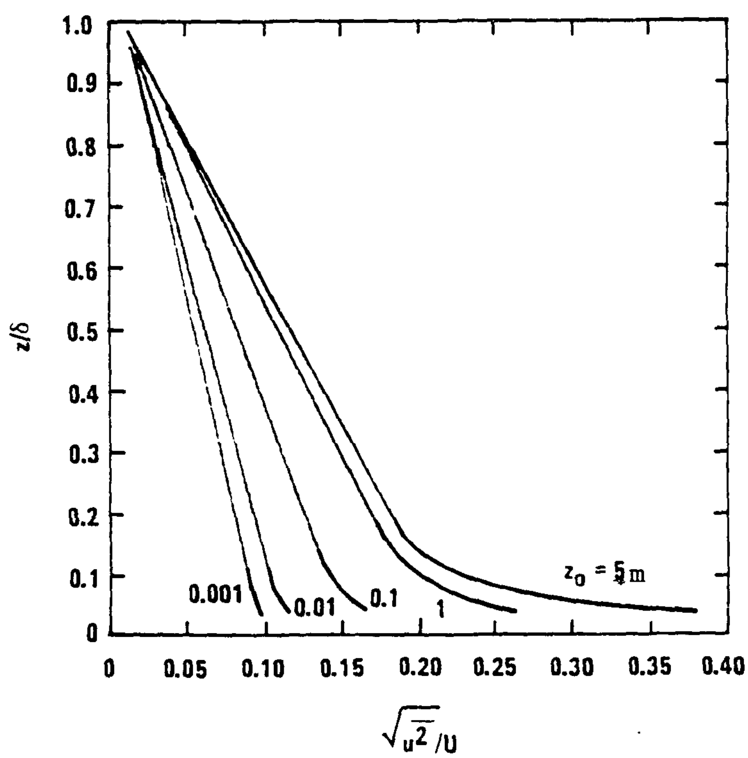

Figure 3. Variation of longitudinal turbulence intensity with height under adiabatic conditions (from Snyder, 1981).

in either the downwind direction and/or the lateral direction may indicate a deficiency in the model design or in the facility operation. No guidance can be presently specified for deciding how much deviation is unacceptable. These profiles should be used only to provide a qualitative assessment.

(c) Report and evaluate the profiles of $-\overline{uw}$ after dividing by its estimated value at the surface. The value at the surface is equal to the surface friction velocity squared u_*^2, which should be comparable to the estimate determined from the velocity profile. These profiles should be used only to provide a qualitative assessment.

Step 4:

(a) Position a model stack, so that the top of the model stack is at a height representing 100 m above the ground. It is desirable at each demonstration of comparability to use the same height. A 100 m high stack was selected because it is believed to be generally representative of the height of stacks for which GEP demonstrations are conducted. A 200 m high stack should be used for situations where GEP stack height is above 170 m. Design the model stack so that its internal diameter is equal to 0.05 times the stack height. Fix the flow rate of a nonbuoyant stack exhaust containing a tracer so that the exhaust velocity is 1.5 times the mean velocity at stack top. This should allow concentration measurements of the tracer to be taken in absence of either plume rise or stack downwash. Concentration measurements for this situation are required to demonstrate comparability to atmospheric dispersion between that estimated using Pasquill-Gifford dispersion parameters for category C and D as presented in Turner (1970).

(b) Take vertical and lateral profiles of concentration through the plume centerline near the quarter intervals between the source and the end of the planned study area (3 profiles each). At least one of these profiles should clearly show the elevated plume centerline height in order to provide an evaluation of the represenative plume rise near the source. Otherwise, an additional profile is necessary. Take a ground-level longitudinal profile of concentration downwind along the surface ground-level centerline to the end of the study area (1 profile). Determination of the surface ground-level centerline should be supported by several ground-level concentrations in the lateral.

(c) Convert model concentrations to equivalent field values with the form $\chi U_s/Q$ (m^{-2}). Plot each vertical and lateral profile of concentration measurement separately along with plume estimates for both Pasquill-Gifford category C and D (Turner, 1970). Use the mean wind speed at the height of the top of the stack U_s as the reference wind speed. The distribution of measured values should fall between the two estimated distributions. Estimated plume distributions incorporating estimated dispersion parameters may be presented. Distinct elevated centerline concentrations should fall between the estimates.

Plot the ground-level longitudinal profile of concentration measurement along with plume estimates for both Pasquill-Gifford category C and D (Turner, 1970). The distribution of measured values should fall between the two estimated distributions with an additional allowance where these two distributions overlap as presented in Figure 4. The dashed lines in Figure 4 allow a factor of two differences in the overlapping region. The concentrations should fall between the estimates at least downwind to the distance of maximum ground-level concentration. It is critical that the ground-level concentration measurement here and the above vertical and lateral concentration measurement not be representative of estimates for more stable situations than category D. Representation by categories more unstable than C are not considered critical since a determination of the GEP stack height will likely be less than that resulting under more stable conditions since the more turbulent atmospheric flow should somewhat overshadow the local building/terrain effect.

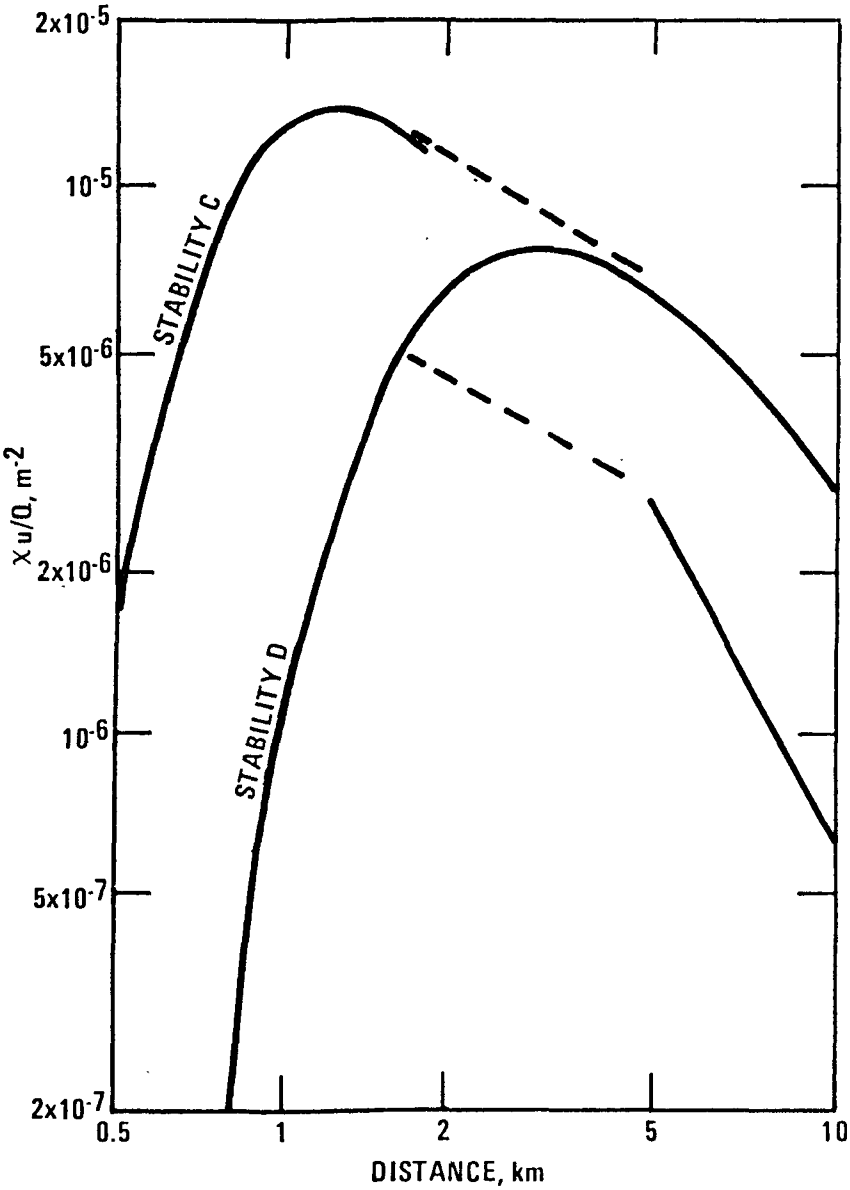

Figure 4. Ground-level concentration with distance for a 100m high plume, estimated with Pasquill-Gifford dispersion parameters for stability category C and D (Turner, 1970).

4.2 Determination of GEP Stack Height

Requirements and procedures for evaluating the model boundary layer characteristics and dispersion for the actual situation are specified below. The results of the previous section establish fluid model comparability to atmospheric dispersion as estimated by recommended mathematical models in the absence of buildings, other structures or large roughness, and/or elevated terrain. Differences between the model boundary layer characteristics and dispersion for the standard situation established in the previous section and the actual situation analyzed below should be related to real expected differences in the field due to the effects of buildings, other structures or large roughness, and/or elevated terrain.

4.2.1 Demonstration of Adverse Effects

The procedure for demonstration and documentation of the adverse effects of buildings and/or elevated terrain nearby the source is outlined below.

Step 1: Place the model topography into the test facility.

(a) For modeling the situation of a few isolated buildings in flat terrain, this is a simple matter. The buildings are simply immersed in the boundary layer designed for satisfying the requirements of Section 4.1.3.

(b) Additional complexity arises for a model of flow over a general urban area and/or elevated terrain. In addition to constructing the model of buildings and/or elevated terrain, surface roughness used in covering the model and general roughness elements upwind of the model to provide appropriate boundary layer characteristics for the situation may be different from those used in the atmospheric dispersion comparability test (Section 4.1.3.).

(c) Report a detailed description of the fluid model.

Step 2:

(a) Take profiles of mean velocity and longitudinal turbulence intensity as in Step 2 (b) Section 4.1.3 (3 profiles each).

(b) Take profiles of mean velocity and longitudinal turbulence intensity as in Step 2 (c) Section 4.1.3 (4-6 profiles each).

(note) There is no need to repeat measurements that would have values identical to those satisfying requirements in Section 4.1.3. (i.e., measurement in the same boundary layer beyond the influence of the building and/or terrain).

Step 3:

(a) Follow Step 3 (b) Section 4.1.3 to determine the model values of z_o, u_*, and p. They should be consistent with guidance presented in Table 1 and Figure 1. Specific guidance for flow over areas of elevated terrain is not available since little data correlating the flow characteristics to the height and separation distances of terrain features has been taken. In general, z_o in areas with elevated terrain should be much larger than the largest values found in Table 1. Significant differences may be found at each location due to differences in the local surface roughness. A discussion of such differences should be presented in the study report.

(b) Follow Step 3 (c) Section 4.1.3.

Step 4: Test for Reynolds number independence.

(a) For sharp-edged obstacles having a Reynolds number $U_H L/\nu$ greater than 11,000, no demonstration test is required.

(b) Where the effects of flow over elevated terrain or smooth-shaped obstacles are being evaluated, a Reynolds number test is required. A full evaluation of Reynolds number independence would require a demanding research project for each situation. The simple test required here should, however, be sufficient enough to provide a critical evaluation. Position a small source emitting a tracer at the site of the GEP stack in question at a height equal to the building or elevated terrain whose effects are in question. The source should be nonbuoyant and have no plume rise. Take a longitudinal surface-level profile of concentration along the downwind direction. Repeat the profile after at least doubling the freestream wind speed U_∞. Take a vertical profile of the mean velocity at the site of the stack for this new situation. Plot and compare the two profiles of concentration $\chi U/Q$ (m^{-2}) using the freestream wind speed as the reference speed. Differences in concentration should not be greater than 10 percent. Reconsideration of the model design is necessary where greater differences are observed.

Step 5: An evaluation of the plume from the stack in question must be made. In general, the fluid modeler should first examine the plume through a visualization technique, i.e., photographs of smoke exhaust. Then a decision can be made as to the height for which GEP credit can be justified. Photographs and/or measured data taken as part of this process must be included in this report. Full documentation as outlined below is required for the actual determination of GEP stack height.

(a) Take vertical and lateral profiles of concentration through the plume centerline at positions one-fourth and one-half of the distance between the source and the end of the study area. Also, do the same at the end of the study area and at the position of maximum ground-level concentrations. The value of maximum ground-level concentration must be unquestionably determined. This requires a longitudinal surface-level profile along the plume centerline, supported by 2 to 4 partial lateral profiles including one across the position of maximum ground-level concentration.

In some situations, it may be necessary to model at a scale such that the likely maximum ground-level concentration falls downwind beyond the modeled area. This is very undesirable, and should be avoided whenever possible. Before such an approach is planned, the agency should first review a proposal, discussing its necessity. The diffusive characteristics for a limited region beyond the modeled area may be obtained by extrapolating the measured values, only for situations of flow over generally homogeneous terrain and/or uniform urban environments. For these situations, additional vertical and lateral profiles of concentration at the position three-fourths between the source and the end of the study area should be made in lieu of measurements at the maximum. Extrapolation should be limited to distances equivalent to one-half the distance between the source and end of the modeled area. Ground-level concentration profiles for several stack heights having their maximum value falling within the modeled area should be made. These profiles can be used to extrapolate a maximum value for higher stack heights, and support the value obtained by extrapolating the measured vertical and lateral profiles of concentration.

(b) Convert model concentrations to equivalent field values with form $\chi U_s/Q(m^{-2})$. Take the mean wind speed at the height of the top of the stack U_s as the reference wind speed. Report each vertical profile of concentration measurement. In absence of reflection from the surface, the plume centerline can be estimated as the vertical position of the maximum concentration. At least one value must be compared to the estimated plume rise as discussed in Section 4.1.2. Additional vertical profiles must be measured if the above required profiles do not provide sufficient information. Report each vertical and lateral profile of concentration measurements separately along with estimated plume distributions incorporating estimated dispersion parameters.

In areas of elevated terrain downwind from the source, such estimates may be difficult and perhaps meaningless. In these instances a discussion relating the plume behavior to anticipated effects of the terrain is needed. Plot the longitudinal and lateral profiles of concentration measurements.

The maximum must be unquestionably determined. Two repeated measurements at the positions of the maximum should be taken and reported as support that the concentration does, in fact, represent the steady-state average. Differences in the three concentrations should not be greater than 10 percent of their values.

In some situations of flow over generally homogeneous terrain and/or uniform urban environments, the maximum value may be obtained by extrapolation as discussed above. For these instances, it is necessary that the appropriate dispersion parameters can be derived from the vertical and lateral profiles of concentration measurements. The maximum ground-level concentration can then be estimated by inserting the derived dispersion parameters into the Gaussian plume formula (Turner, 1970). Extrapolation of measured longitudinal ground-level profiles should support the estimated maximum ground-level concentration. Approval for such a study plan must be granted by the reviewing agency prior to the study to allow agency experts to provide a critical assessment.

4.2.2 GEP Stack Height

The stack height for which full documentation has been provided in the previous sub-section is GEP if the maximum surface-level concentration is 40 percent or more in excess of the maximum in the absence of downwash, wake, or eddy effects produced by nearby structures or terrain. The procedure for validating the proposed GEP stack height is presented below.

Step 1:

Remove the building(s) or elevated terrain in question. This is a simple matter in the case of buildings nearby the stack. The situation near elevated terrain is complicated since removal of the terrain feature in question may result in an unrealistic discontinuity in the topography. A similar difficulty arises where a high plateau is upwind of the source. In such instances it may be necessary to remove all upwind terrain and replace its area with appropriate surface roughness. The surface roughness elements must be shown to result in an appropriate z_o and u_*. This requires that a vertical profile of mean velocity, longitudinal turbulence intensity, and shear stress be measured upwind of the source at the position where the elevated terrain feature was located. Estimate z_o and u_* guided by Step 3 (a,b) Section 4.2.1. The boundary layer should be appropriately characterized as with the actual topography.

Step 2:

Determine the maximum ground-level concentration. Document fully as required by Step 5, Section 4.2.1.

Step 3:

The proposed stack height is creditable as GEP if the maximum ground-level concentration determined in Step 5, Section 4.2.1 is at least 40 percent in excess of the maximum ground-level concentration determined in Step 2 above. Discussion relating the increased maximum ground-level concentration measured in the presence of the building(s) or terrain in question to anticipated effects due to downwash, wakes, or eddies should be presented in the report.

5.0 REPORT CHECKLIST

The fluid modeling study report should include the five items that are outlined below. The report should completely document the design and operation of the model study. Three tests should be conducted. The data collected for these tests must allow for conclusions to be drawn concerning the atmospheric conditions simulated by the fluid model, and the cause of increased maximum ground-level concentrations for a stack in the presence of nearby building(s) and/or terrain. The height of the stack examined in the study is creditable as GEP if the maximum ground-level concentration is at least 40 percent greater in the presence of the nearby building(s) and/or terrain than that measured in their absence. The report should include at least the following:

1. A detailed topographic map and discussion concerning the selection of the size of the modeled area and meteorological parameters.

2. Discussion of model design and similarity criteria.

3. An evaluation of the test facility in the absence of building(s), other surface structures, or large roughness and/or elevated terrain including:

(a) a detailed description of the fluid model including features of the scale model, surface roughness, velocity profile, and method used to provide the fully developed boundary layer,

(b) one representative vertical profile of mean temperature if model free-stream speed is less than 3 m/s,

(c) three vertical profiles of mean velocity,

(d) three vertical profiles of longitudinal and vertical turbulence intensity,

(e) three vertical profiles of $\overline{uw}$,

(f) four lateral profiles of mean velocity,

(g) four to six lateral profiles of longitudinal turbulence intensity,

(h) effective surface roughness length z_0, friction velocity u_*, and velocity power law index p, determined by evaluating the mean velocity profiles and the shear stress profile,

(i) three vertical and lateral profiles of concentration through the elevated centerline of the plume,

(j) one ground-level longitudinal profile of concentration downwind along the plume centerline,

(k) evaluation of comparability of measured concentrations to plume estimates for Pasquill-Gifford category C and D (Turner, 1970),

(l) evaluation of the measured elevated centerline of the plume.

4. Documentation for the GEP stack height test in the presence of building(s), other surface structures, or large roughness and/or elevated terrain should include:

(a) detailed description of the fluid model including features of the scale model, surface roughness, velocity profile, and the method used to provide the fully developed boundary layer,

(b) three vertical profiles of mean velocity,

(c) three vertical profiles of longitudinal and vertical turbulence intensity,

(d) three vertical profile of $\overline{uw}$,

(e) effective surface roughness length z_0, friction velocity u_*, and velocity power law index p, determined by evaluating the mean velocity profiles and the $\overline{uw}$ profiles,

(f) possible test for Reynolds number independence,

(g) four vertical and lateral profiles of concentraion through the elevated centerline of the plume including profiles at the position of maximum ground-level concentration,

(h) one ground-level longitudinal profile of concentration downwind along the plume centerline at ground-level,

(i) two to four lateral ground-level profiles including one at the position of maximum ground-level concentration,

(j) discussion supporting the unquestionable determination of the maximum ground-level concentration,

(k) evaluation of the measured elevated centerline of the plume.

5. Documentation for the GEP stack height test in the absence of building(s) or elevated terrain considered in justifying the stack height should include:

(a) the same as steps (g), (h), (i), (j), and (k) above,

(b) discussion relating the increased maximum ground-level concentration measured in the presence of the building(s) or elevated terrain in question to anticipated effects due to downwash, wakes, or eddies,

6. A separate section or appendix describing the fluid modeling facility, instrumentation used in the conduct of the study, and their normal operating conditions and associated parameters.

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TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

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15. SUPPLEMENTARY NOTES

16. ABSTRACT

Guidelines for developing and reviewing fluid modeling studies for determining good engineering practice stack height. Includes review of appropriate fluid modeling theory and a specific report requirement checklist.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution Good Engineering Practice Stack Height Physical Modeling Fluid Modeling	Air Pollution Control	13-B

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